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UCRL-TR-226946

# INSPECTION SHOP: PLAN TO PROVIDE UNCERTAINTY ANALYSIS WITH MEASUREMENTS

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December 21, 2006

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

# Inspection Shop: Plan to Provide Uncertainty Analysis with Measurements

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Version 2

November 2006

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## **1.0 Introduction**

The LLNL inspection shop is chartered to make dimensional measurements of components for critical programmatic experiments. These measurements ensure that components are within tolerance and provide geometric details that can be used to further refine simulations. For these measurements to be useful, they must be significantly more accurate than the tolerances that are being checked. For example, if a part has a specified dimension of 100 millimeters and a tolerance of 1 millimeter, then the precision and/or accuracy of the measurement should be less than 1 millimeter. Using the “10-to-1 gaugemaker's rule of thumb,” the desired precision of the measurement should be less than 100 micrometers. Currently, the process for associating measurement uncertainty with data is not standardized, nor is the uncertainty based on a thorough uncertainty analysis.

### **1.1 Project goal**

The goal of this project is to begin providing measurement uncertainty statements with critical measurements performed in the inspection shop. To accomplish this task, comprehensive knowledge about the underlying sources of uncertainty for measurement instruments need to be understood and quantified. Moreover, measurements of elemental uncertainties for each physical source need to be combined in a meaningful way to obtain an overall measurement uncertainty.

### **1.2 Why is uncertainty analysis important?**

The measurements being made by the inspection shop are used to make decisions about accepting or rejecting critical parts. The inspection shop is widely used within Engineering, and the measurements are typically accepted as being “sufficiently” accurate. This assumption should be verified by a measurement uncertainty analysis – this is the accepted practice at all of the other NNSA sites. There is a significant risk to Lab programs if measurement data is in error, which could lead to the use of components in experiments that are outside of specifications.

### **1.3 Gaining a fundamental understanding of the inspection shop**

Prior to beginning the uncertainty analysis plan, much work was done to gain a fundamental understanding of the inspection shop and its operation. Several areas were studied: 1) the role of the inspection shop (as defined in various DOE/NNSA documents) was reviewed and analyzed; 2) the critical equipment in the inspection shop was investigated to understand uses and limitations; and 3) the relationship between the Primary Standards Lab (PSL) at Sandia National Laboratory in New Mexico and the inspection shop at LLNL was examined. The results of that study were documented in a report, “Inspection Shop Capabilities.” That report should be read prior to reviewing this report.

### **1.4 What is in this report?**

This report describes a plan for bringing uncertainty analysis into the inspection shop. It covers 1) the methodology behind the uncertainty analysis, 2) uncertainty analysis methods and tools used by the National Institute of Standards and Technology (NIST)

and PSL, and 3) the beginning of an uncertainty analysis of the Precision Inspection Shell Measuring Machine (PrISMM).

## **2.0 The plan**

There are over a dozen instruments in the inspection shop that are on the critical inspection equipment list. These instruments need to have their measurement uncertainties determined. The machines will be broken down into three groups: shell measurement instruments (Precision Inspection Shell Measuring Machine (PrISMM) and the rotary contour gage), Coordinate Measurement Machines (there are six CMMs in the inspection shop), and other measurement instruments (Moore measurement machines, Y/Z machine, etc.). Uncertainty analysis will begin with the rotary contour gage and the PrISMM because of their programmatic importance. Next, the Coordinate Measurement Machines will be analyzed. Finally, the remaining machines will be analyzed. After completion of the analysis, measurement uncertainty data sheets would be written and provided to inspection shop customers. Moreover, with the enhanced knowledge obtained by completing thorough uncertainty analyses, improvements would be made, where appropriate, to the certification and accuracy of the existing machines.

## **3.0 A quick introduction to uncertainty analysis**

Personnel at the National Institute of Standards and Technology (NIST) have written papers and guides on measurement uncertainty analysis for both NIST personnel and outside personnel wishing to calculate measurement uncertainty. A quick introduction to that material is given here. The reader is encouraged to review the actual NIST papers (see reference section) to get a better understanding of the subject.

The calculation of uncertainty for a measurement is an effort to set reasonable bounds for the measurement result according to standardized rules. To accomplish this task, all significant uncertainty sources need to be known. Once known, they need to be classified as either Type A or Type B uncertainties. Type A uncertainties are evaluated statistically. Uncertainties evaluated by any other method are called Type B. A type B evaluation of uncertainty is usually based on scientific judgment using all the relevant information available (e.g., previous measurement data, manufacturing specifications, and uncertainty data from handbooks).

Typically the Type B uncertainty is bound between a maximum and minimum value. A uniform (i.e., rectangular) probability distribution can be assumed to represent the uncertainty; this is usually a conservative approach. Other probability distributions can be used as well, but they should be justified if used. Figure 1 shows a uniform distribution. From the uniform distribution, an equivalent standard uncertainty can be calculated. This value can be used with the other equivalent standard uncertainties and/or Type A uncertainties to calculate a combined uncertainty.

The combined uncertainty of a measurement is taken to represent the estimated standard deviation of the measurement. It is obtained by combining the individual standard

uncertainties using the “law of propagation of uncertainty” method (this method is also referred to as the “root-sum-of-squares” or “RSS” method).

The calculated combined uncertainty represents one standard deviation. In other words, this means there is a 68% chance that the actual measurement is covered by the calculated combined uncertainty. Typically, the calculated uncertainty is multiplied by a coverage factor to obtain an expanded uncertainty. Usually a coverage factor of 2 (95% coverage) or 3 (99% coverage) is used.

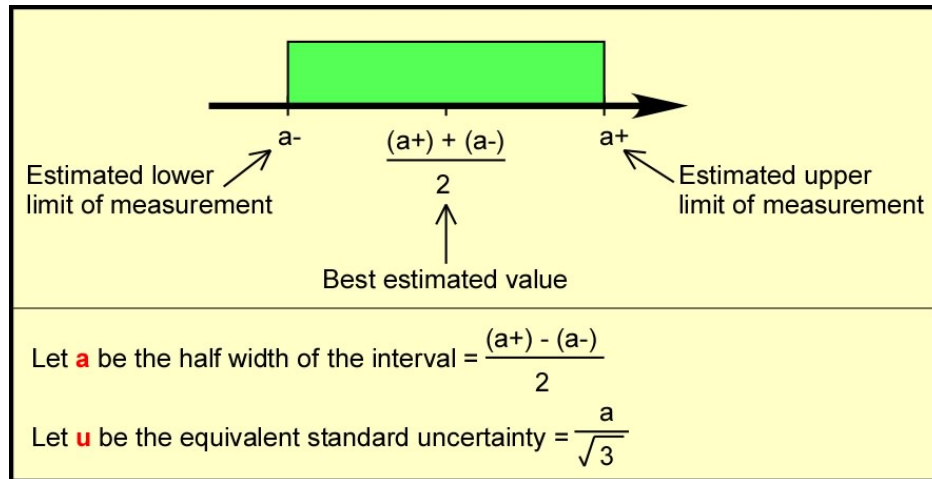


Figure 1: Calculating equivalent standard uncertainty for a Type B uniform distribution

When reporting a measurement uncertainty several pieces of information should be given. Here is a minimum acceptable list:

- the expanded uncertainty and the coverage factor used;
- a list of all uncertainty components and their respective uncertainty type;
- a description of how each uncertainty component was evaluated; and
- an explanation of why a different coverage factor (other than 2) was used.

## 4.0 Methodology

As described in the inspection shop capabilities report, the inspection shop is responsible for many metrology instruments. A large percentage of these inspection instruments are on the critical M&TE (Measurement & Testing Equipment) list. These instruments need to be regularly certified. In some cases, the inspection shop personnel certify the equipment using procedures written and approved by LLNL personnel and also approved by the Primary Standards Laboratory in New Mexico. In other cases, certified vendors certify the instruments; this is common for the Coordinate Measuring Machines (CMMs) in the inspection shop. In either case, extensive instrument measurements are typically made to determine if the different components (e.g., slides, joints, etc.) of the instrument are functioning correctly. For example, the certification instructions for the Rotary Contour Gage list twelve measurements that need to be made at specified regular intervals – ever four years for this machine. Some of these measurements include

straightness of slides, alignment of axes, and radial errors of rotary axes. The measurements can be compared to the previous measurements to determine if the instrument has changed since the last certification. If large changes have occurred, then three steps should be taken: 1) the instrument should be recalibrated; 2) the part measurements made between the two certification checks should be re-evaluated; and 3) the interval between future certification checks should be shortened. The yellow boxes in the flowchart figure (Figure 2) represent the current certification steps for the critical equipment in the inspection shop.

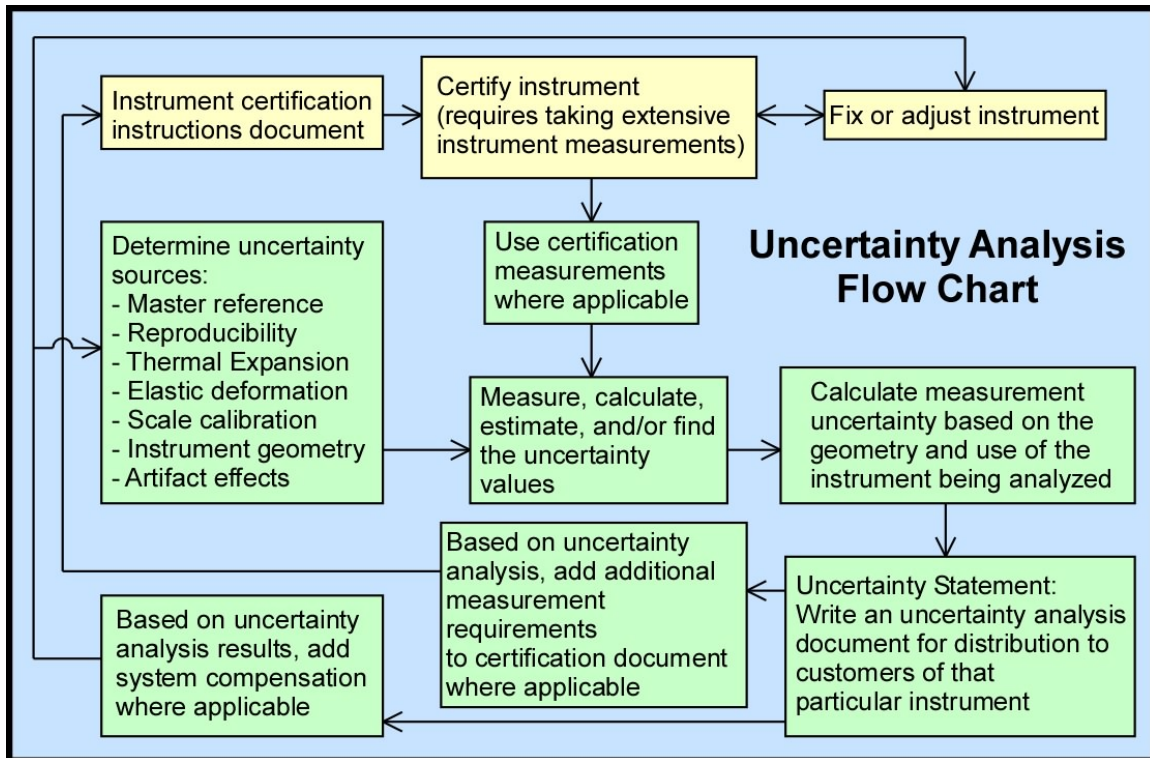


Figure 2: Uncertainty analysis flowchart

The data from the instrument certification tests can be used to help create an instrument uncertainty analysis – the steps need to accomplish this task are represented by the green boxes in Figure 2. As can be seen in the figure, several major steps are needed to create and maintain the uncertainty analysis of an instrument. These steps are described in more detail below.

#### 4.1 Determine uncertainty sources

Prior to creating an uncertainty analysis, all of the uncertainty sources must be identified. For a complex measurement tool, such as the Rotary Contour Gage, listing the uncertainty sources can seem like an overwhelming task. Some of the large uncertainty sources that need to be considered include the uncertainty of the references, thermal expansion, elastic deformations, instrument geometry, scale calibration, and repeatability.



## **4.2 Determine the uncertainty associated with the uncertainty source**

After identifying the uncertainty sources, uncertainty values must be assigned to those sources. This can be accomplished using manufacturing specifications, component testing, estimation, etc. Regardless of the method used to determine the uncertainty values, the logic behind the decisions should be clearly stated.

The certification test results for the critical equipment should be used at this step because many of the tests that one would like to conduct to determine the uncertainty of an instrument have already been accomplished as a requirement of the instrument certification.

## **4.3 Calculate the measurement uncertainty of the instrument**

After identifying the uncertainty sources and assigning uncertainty values to those sources, the next step is to calculate the combined uncertainty. In some cases, this can be as simple as apply a Root of the Sum of the Squares (RSS) calculation. However, for more complicated measurement instruments, the effect of an uncertainty source on the combined measurement uncertainty may not be obvious. For example, measurement instruments can be insensitive to some axis error motions. Each source needs to be individually evaluated to determine its effect on the instruments ability to make a measurement. Moreover, the logic used in determining the relationship between the uncertainty source and combined uncertainty needs to be clearly stated.

## **4.4 Create an uncertainty statement for the instrument**

After completing the uncertainty analysis calculations, which should be kept with the certification paperwork for the instrument being evaluated, the results of the analysis need to be summarized so that inspection shop customers have access to the uncertainty information.

## **4.5 Improve the certification instructions for the instrument**

After completing the uncertainty analysis, it will be clear which sources have the largest effect on the combined uncertainty. Using this information, the certification procedures should be reviewed to see if the proper measurements are being made. If there are oversights in the certification procedures, the certification procedures should be revised to correct the oversights.

## **4.6 Improve the instrument using the uncertainty analysis**

Armed with the uncertainty analysis, the inspectors know the largest contributors to the combined uncertainty of an instrument. This can aid them when trying to improve an instrument. The largest uncertainty contributors should be the focus of any effort to improve the accuracy of an instrument.

## **5.0 Initial Uncertainty Analysis Work on PrISMM**

The Precision Inspection Shell Measuring Machine (PrISMM) is currently being brought into operation to replace the 40-year-old Rotary Contour Gage (RCG). PrISMM was

designed to measure shells to a higher accuracy than the RCG; moreover, it was designed to collect significantly denser data sets. Figure 3 shows PrISMM and highlights its four axes: the upper z axis, the lower z axis, the y axis, and the rotary axis. Figure 4 shows a simple schematic of the machine and its laser interferometers that provide axis position.

As can be seen in these two figures, PrISMM uses two air-bearing LVDT probes to measure the inside and outside of a shell. The shell sits on three tabs attached to the rotary axis. The rotary axis rotates the shell so that the probes can measure perturbations in roundness. The y axis and upper x axis position the top probe to make profile measurements of the outside of the shell. The y axis and lower z axis position the bottom probe to make profile measurements of the inside of the shell. The inside and outside measurements are not made simultaneously. The shell thickness can be calculated using the inside and outside shell measurements.

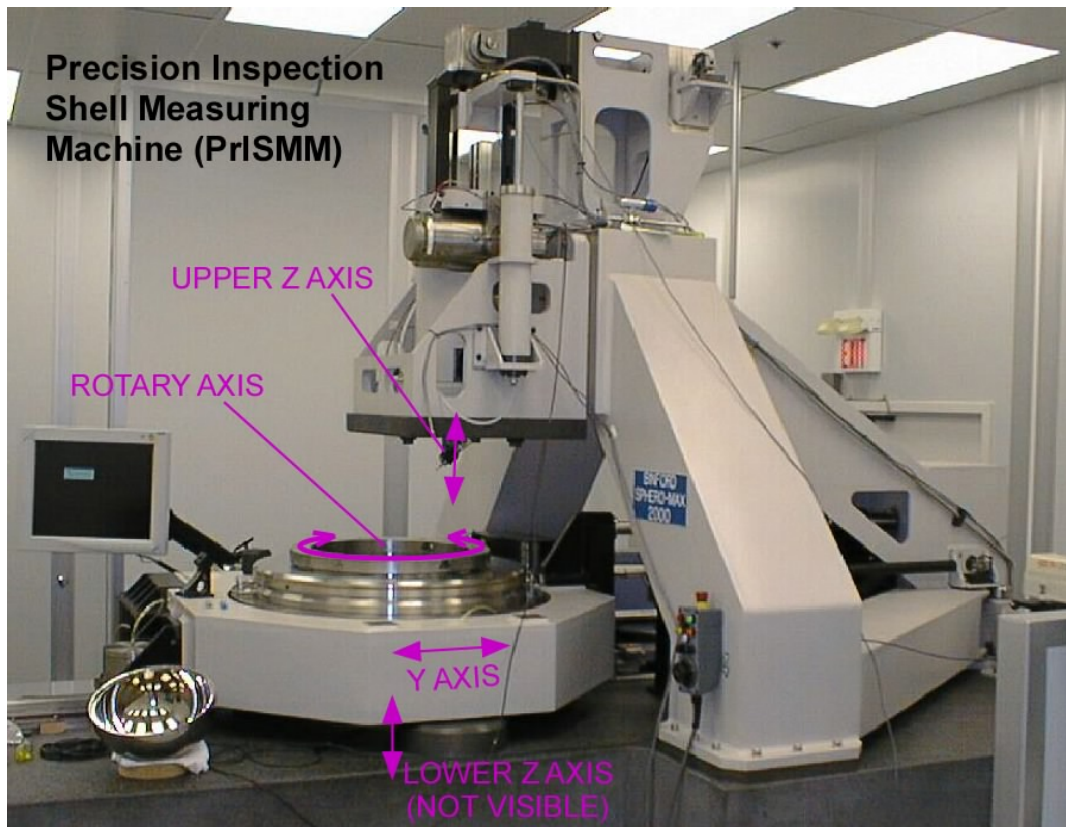


Figure 3: The Precision Inspection Shell Measuring Machine (PrISMM)

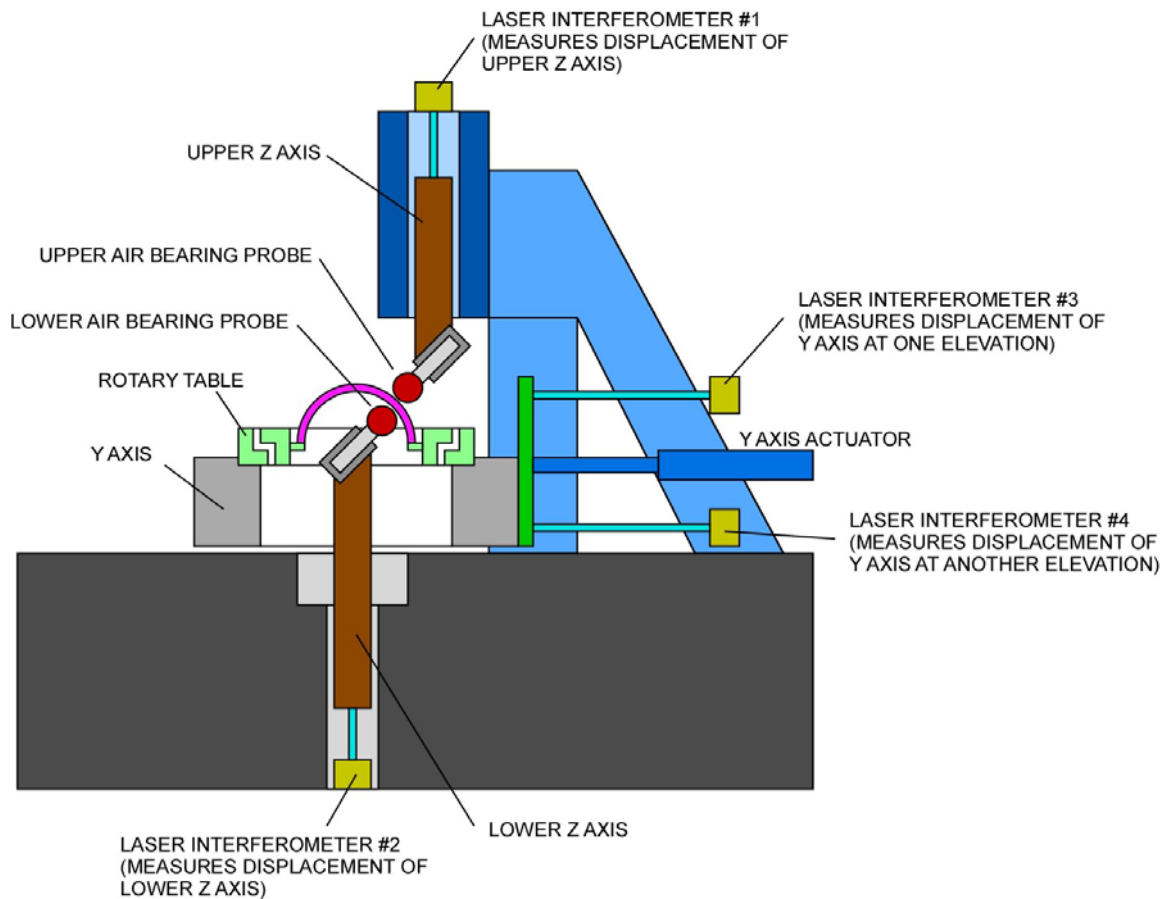


Figure 4: A schematic of The Precision Inspection Shell Measuring Machine (PrISMM)

## 5.1 Certification

In order for PrISMM to become a critical inspection instrument, it must be certified. Certification entails proving that the machine is operating as intended. Typically, two methods are used to certify a measurement machine: 1) use a testing artifact and 2) measure the performance of individual machine components to see if they are working as intended.

Using a testing artifact is a “feel good” method. If a test part is known to be a certain size and the measurement machine being tested provides nearly identical measurements, the inspector will have significantly more faith in the measuring ability of that machine. However, there are problems with using a testing artifact: 1) the testing artifact must be fabricated – this can be costly; 2) the testing artifact must be accurately measured on a well characterized machine – this can be very costly; 3) accurately measuring the testing artifact on the machine being tested only proves that the machine can measure that part or parts of similar size and composition accurately; and 4) measuring a testing artifact doesn’t tell the inspector what components of the machine are contributing the largest errors; hence, it doesn’t tell the inspector where to focus effort when trying to improve or fix the measurement machine.

The other method, testing the individual machine components, provides additional knowledge not available from using a testing artifact; however, this method suffers from other problems: 1) it can be time consuming to measure all of the different components of a machine (e.g., axis alignment, straightness of slides, rotation errors, etc.) and 2) the measurement uncertainty of the machine isn't directly measured – it must be calculated via an uncertainty analysis. Although not perfect, the benefits of this method are substantial: 1) regular testing of the components provides historical data on the operating condition of the machine; 2) the component measurements (in conjunction with an uncertainty analysis) will show the largest error contributors in the measurement machine; 3) the component measurement data can be used to compensate for repeatable error motions and, therefore, improve the machine; and 4) the component data can be used in a measurement machine uncertainty analysis that covers the full operating capacity of the machine (e.g., the full working volume of a CMM).

Ideally both methods should be used to certify a machine; however, this is not always carried out because of time, cost, and personnel limitations. For PrISMM, both methods are being used. Two testing artifacts were recently fabricated at LLNL (a profile artifact and a thickness artifact) to implement the first certification method. They were sent off to the National Institute for Standards and Technology (NIST) to be measured. Soon, they will be measured on PrISMM, and the measurement results will be compared.

To complete the second certification method, the components that contribute to the overall measurement uncertainty of the machine need to be identified, measured, and combined using uncertainty analysis. In the next section, the PrISMM uncertainty sources are identified.

## **5.2 PrISMM uncertainty sources**

Figure 5 shows a hierarchical breakdown of PrISMM uncertainty sources. As can be seen in the figure there are three main uncertainty categories: probe accuracy, process uncertainties, and probe path accuracy. The probe accuracy category covers the measurement uncertainties associated with the LVDT probes. The LVDT portion of the probe has several uncertainty sources associated with its use; the main sources are electric noise, linearity, and thermal stability. The probe tips also contribute to the uncertainty because the size and contour of the probe tips are not exactly known. The probing force also causes uncertainty in the measurement by deflecting the probe and the part being measured. Deflections are expected to be small, however, because air bearing LVDTs have very low probing forces.

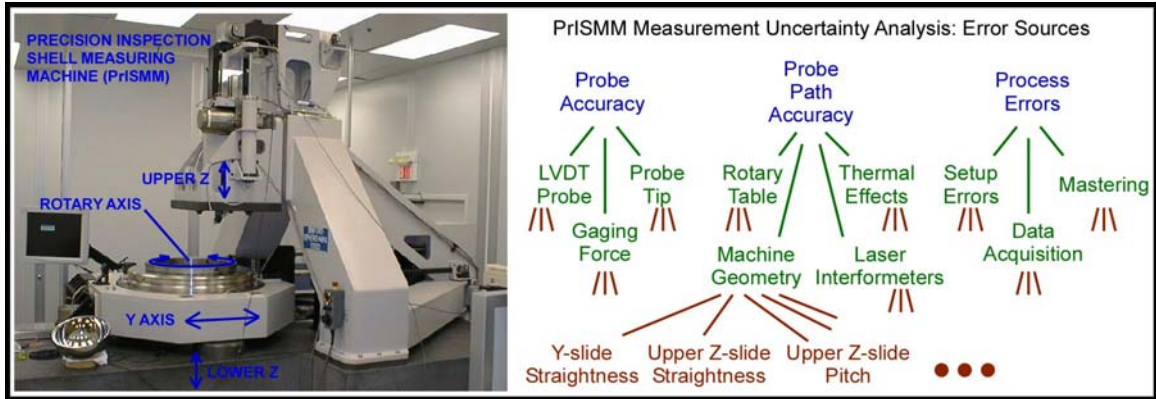


Figure 5: A hierarchical breakdown of the PrISMM uncertainty sources

The next main uncertainty category is processing uncertainties. These uncertainties are not caused by the measuring machine hardware; they are caused by the master reference, setup errors, and data acquisition issues. Setup errors are caused by imperfect part centering and alignment issues. Mastering errors are caused by use of the imperfect master gage ball. Sampling interpolation issues cause the data acquisition errors.

The final uncertainty category, probe path accuracy, is the most challenging of the three categories because it is difficult to identify and place values upon the numerous uncertainty sources. The probe path accuracy is determined by axis alignment, the accuracy of the individual axes, the displacement measuring laser interferometers, load effects, and thermal effects. The laser interferometers have several sources of uncertainty: frequency stability, resolution, index of refraction, and optical/electronic factors. The thermal effects cause the entire machine to shift in space as the temperatures in the machine and environment change. Load effects cause the machine to bend and deflect as the slides are moved. All of the axes need to be aligned relative to each other; hence, there are many uncertainties associated with alignment. The three sliding axes have pitch, yaw, roll, and two displacement uncertainties. The rotary axis has radial, axial, and tilt uncertainties. All of these uncertainties need to be identified, understood, and measured or estimated. In the next section, the measurement of the straightness of the upper z axis is described as an example of a typical measurement used for certification of an inspection machine.

### 5.3 Measurement example: Straightness of the upper z axis

The straightness of the upper z axis in the y direction directly affects the accuracy of the PrISMM when using the upper measurement probe. Therefore, its uncertainty needs to be quantified to calculate the combined uncertainty of the machine. Because PrISMM is both an advanced computer-controlled machine and has highly repeatable axes, the repeatable straightness errors can be entered into the controller and compensation can be used to improve the accuracy of the machine. Figure 6 shows the setup for measuring the straightness of the upper z axis in the y direction.

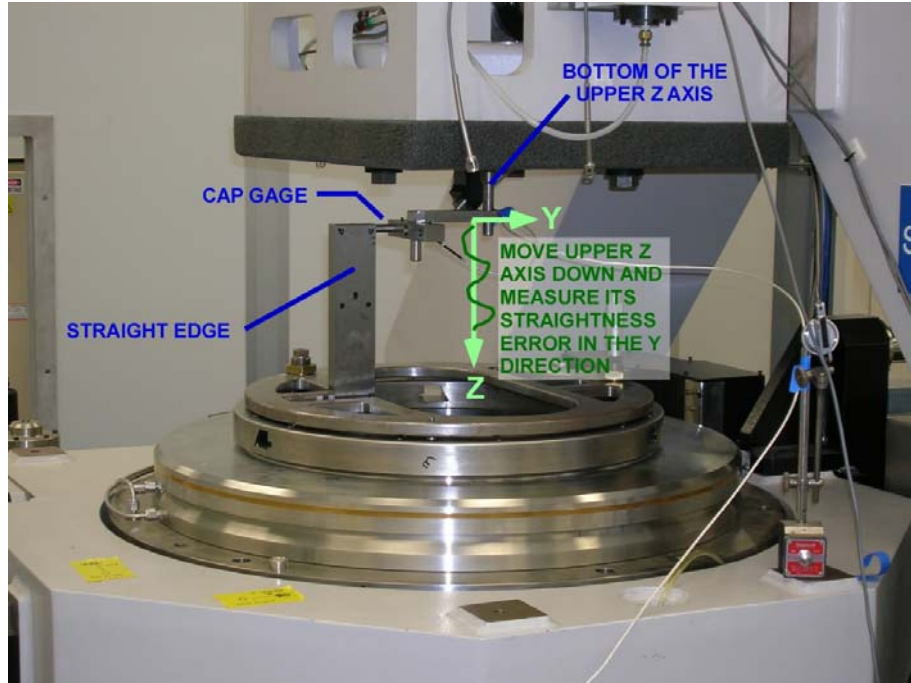


Figure 6: Setup for measuring the straightness of the upper z axis in the y direction

## 6.0 Conclusion

This report described a plan for bring uncertainty analysis to the inspection shop. Methodology, an introduction to calculating uncertainty, and an example (i.e., PrISMM) were used to aid the reader in understanding the plan. The reader is encouraged to read the references to gain a further understanding of the material presented in this report.

## 7.0 References

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